*NON - CONTACT*

(54) **Automatic tip approach method and apparatus for scanning probe microscope**

Verfahren und Vorrichtung zur automatischen Annäherung der Spitze eines Rastermikroskops

Méthode pour l'approche automatique d'une pointe et appareil pour un microscope à balayage

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(56) References cited:
WO-A-89/12805    US-A- 5 025 658

• JOURNAL OF APPLIED PHYSICS. vol. 61, no. 10,
15 May 1987, New York US, pp. 4723-4729; Y.
MARTIN et al.: 'Atomic force microscope-forc
mapping and profiling on a sub 100 Angstrom
scale'
• PATENT ABSTRACTS OF JAPAN, vol. 15, no.
175 (E-1063) 2 May 1991; & JP-A-30 40 355; &
US-A-5 142 145 (MASATOSHI YUSATAKE) 25
August 1992
• JOURNAL OF APPLIED PHYSICS, vol. 69, no. 2,
15 January 1991, New York US, pp. 668-673; T.R.
ALBRECHT et al.: 'Frequency modulation
detection using high-q cantilevers for enhanced
force microscope sensitivity'
• JOURNAL OF VACUUM SCIENCE AND
TECHNOLOGY : PART A, vol. 6, no. 2, March
1988, New York US, pp. 266-270; R.
ERLANDSSON et al.: 'Atomic force microscopy
using optical interferometry'
• JOURNAL OF VACUUM SCIENCE AND
TECHNOLOGY : PART B, PART II, vol. 9, no. 2,
March 1991, New York US, pp. 1318-1322; N.
UMEDA et al.: 'Scanning attractive force
microscope using photothermal vibration'
• APPLIED PHYSICS LETTERS, vol. 55, no. 17, 23
October 1989, New York US, pp. 1718-1720; K.
TAKATA et al.: 'Tunneling acoustic microscope'

EP 0 574 234 B1

## Description

The present invention relates to a method and apparatus for automatically positioning a micromachined, micro-miniature sensing probe for a scanning probe microscope (SPM). More particularly, the invention relates to a method and apparatus for positioning a sensing probe with increasingly precise incremental steps, while maintaining a non-contact mode of operation between the sensing probe and target surface during the entire process.

Scanning probe microscopes (SPMs) are instruments that provide high resolution information about surface contours. Vertical movement of a sensing probe, in response to a raster scanning procedure of the sensing probe across a target surface, is used for determining the target surface contour. Implementations of SPM devices are based on the interaction of forces including atomic, electrical potential, magnetic, capacitive, or chemical potential to maintain a constant probe to target surface gap, or distance. One common use of these devices is imaging with some types of SPMs having the capability of imaging individual atoms.

In addition to imaging surface contours, SPMs can be used to measure a variety of physical or chemical properties with detail over the range from a few Angstroms to hundreds of microns. For these applications, SPMs can provide lateral and vertical resolution that is not obtainable from any other type of device. Examples of applications include imaging or measuring the contour properties of transistors, silicon chips, disk surface, crystals, cells, or the like.

In order to provide for optimal operation of the SPM, a scanning probe is positioned over a target surface at a distance within the same order of magnitude as molecular geometries. That is, a distance of one or two atoms, or an order of magnitude of tens of Angstroms. Prior art methods using sensing probes have typically positioned the probe manually at a desired distance from the target surface or by allowing the probe to make contact with the target surface and subsequently backing the probe away from the target surface. Such an embodiment is disclosed, for example, in US Patent 5,025,658.

The prior art methods of positioning the scanning probe tip have several shortcomings. The initial positioning process for tolerances in the microscopic range is one that is inherently critical. As noted, optimal scanning probe microscope operation necessitates positioning the sensing probe above the target surface at a distance within an order of magnitude of molecular geometries. The necessity of human interaction results in questionable reliability and, further, is time consuming. In addition, allowing the scanning probe to make physical contact with the target surface during calibration or set up may damage, or otherwise make unusable, the target device/substance or scanning tip.

JP-A-3040355 discloses a scanning tunnelling microscope in which a probe is moved to the tunnelling region in a short time using a high-speed coarse motion control on the basis of focal distance measured by an optical microscope.

It is therefore desirable to provide a scanning probe microscope using an automatic initial positioning procedure requiring no operator interaction.

It is also desirable to provide a method of positioning a sensing probe for a scanning probe microscope above the surface of a target surface without making contact with the target surface.

Viewed from one aspect the present invention provides a method for positioning the tip of a sensing probe of scanning probe microscope, relative to a target surface, the tip being mounted on a vibrating cantilever, the method comprising the steps of: moving the sensing probe at a first speed to a first position relative to a target surface, at which first position the sensing probe interacts acoustically with the target surface and a first predefined effect on the amplitude of vibration of the vibrating cantilever is detected by monitoring the amplitude of vibration; and moving the sensing probe at a second speed which is less than said first speed to a second position between the first position and the target surface, at which second position the sensing probe interacts atomically with the target surface and a second predefined effect on the amplitude of vibration of the vibrating cantilever is detected by monitoring the amplitude of vibration.

Viewed from another aspect the present invention provides a scanning probe microscope comprising: a sensing probe comprising a tip mounted on a vibratable cantilever; means for causing the cantilever to vibrate at a predetermined frequency; means for monitoring the amplitude of vibration of the vibrating cantilever; and means, responsive to the monitoring means, for moving the sensing probe at a first speed to a first position relative to a target surface, at which first position said means for monitoring detects a first predefined effect on the amplitude of vibration of the cantilever, and for subsequently moving the sensing probe at a second speed to a second position relative to the target surface, at which second position said means for monitoring detects a second predefined effect on the amplitude of vibration of the cantilever.

In order that the invention may be fully understood preferred embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1 is an exploded perspective view of a tip approach system for a scanning probe microscope;

Fig. 2 is a block diagram illustrating an implementation of a sensing prob positioning system in a scanning probe microscope in accordance with the present invention;

Fig. 3 is a graphical representation of the amplitude of vibration of a vibrating cantilever vs. the tip to target surfac gap according to the present invention;

Fig. 4 is a graph illustrating the ffect of acoustic dampening on a vibrating cantilever;

Fig. 5a is a graph illustrating the effect of Van der Waals forces on the resonant frequency of a vibrating cantilever; and

Fig. 5b is a graph illustrating the change in amplitude of vibration for a dampened vibrating cantilever due to a shift in resonant frequency.

The assembly of Fig. 1 is used in a sensing probe microscope. It includes a base plate 10 which provides a reference surface with respect to which a bimorph sensing probe assembly 12 is moved. A pair a approach actuators 14 (commercially available as IW-701 actuator and manufactured by Burleigh Instruments Inc.) are attached to a holder plate 16 such that the lower most extremity of the approach actuators 14 bear against the upper surface of the base plate 10. The holder plate 16 has a calibrated Z piezo actuator 17 which extends downwardly therefrom and carries, at its lower most end, a microscope objective 13. The piezo actuator 17 is used essentially in a scanning procedure. The microscope objective 13 carries the sensing probe 12 at its lower end. The microscope objective 13 includes an objective lens through which a laser is focused. The function of the objective lens is not critical to positioning the sensing probe 12, and is used essentially for viewing a sample (not shown). This sensing probe 12 is, accordingly, raised and lowered relative to a target surface (not shown) below the sensing probe 12 by actuation of the approach actuators 14 which move the plate 16 up and down with respect to the base plate 10. In the preferred embodiment of the invention, the approach actuators 14 are moved in tandem. In an alternative embodiment, more than two approach actuators 14 may be used with independent movement, and in fact may be desired, in order to adjust positioning or to provide a tilt feature or function. The probe tilting feature of US Patent 5,103,095 is illustrative of a mechanism which is capable of performing this function should it be desired as part of the present system.

Referring next to Fig. 2, a block diagram of the scanning probe microscope control and positioning circuitry is illustrated. The sensing probe 12, comprising a cantilever 18 having a microminiature tip 19 integrally formed or mounted at one end and a small piezoelectric element 24 at the opposite end, is vertically positioned above a target surface 20 of a sample 22. An excitation signal vibrates the cantilever/tip combination at a frequency slightly greater than the resonant frequency of the cantilever 18. The piezoelectric element 24 is used to yield a constant amplitude of vibration of the vibrating cantilever 18. In addition, the piezoelectric element 24 (upon application of an appropriate voltage signal) can also move the cantilever 18, upwardly and downwardly (in a Z direction), with respect to the target surface 20 for very small adjustments (less than one micron). In the preferred embodiment, the piezoelectric element 24 is a bimorph piezoelectric element (i.e., piezoelectric slabs joined together), but may also be either a piezoelectric plate or tube. The piezoelectric element 24 needs to be able to move the tip end of the cantilever 18 up and down about one micron so that the optimal operating point, defined as setpoint gap, may be established.

The amplitude of vibration of the vibrating cantilever 18 is monitored by a heterodyne laser interferometer 30. Laser interferometric techniques are well known, with the output of the interferometer 30 representing the amplitude of vibration of the vibrating cantilever 18, and thereafter supplied to a controller 32 and a analog servo circuit 15. In the preferred embodiment, a heterodyne laser interferometer 30 monitors the amplitude of vibration of the vibrating cantilever, although other monitoring techniques will be recognized by those skilled in the art. Accordingly, a laser source incident upon the vibrating cantilever 18 is reflected back to the laser interferometer 30. The reflected laser light returning from the cantilever 18 is combined with a reference beam that has been frequency shifted 80 Mhz relativ to the tip beam. An interference, resulting in an 80Mhz sinusoidal beat frequency, is phase modulated by the tip vibration. A phase demodulator and lock-in amplifier (part of laser interferometer 30) converts the tip vibration modulation into a voltage $V_a$, which in magnitude is proportional to the tip vibration amplitude.

A control signal output from the controller 32 is provided to a piezo driver 38 which serves to drive the approach actuators 14, either directly or through a smoothing filter 40, to vertically position, control, or maintain the vertical position of the sensing probe 12. The smoothing filter 40 is optionally selectable by the controller 32 and serves to smooth a drive signal generated by the piezo driver 38 and eliminates unacceptable large motion, noise, or spikes that would otherwise cause the sensing probe 12 to be driven into the target surface 20. The approach actuators 14 along with the smoothing filter 40 provide versatile and precise performance including adjustable speed of movement (2 mm/sec to 10 microns/sec), rapid deceleration, fine resolution, uniform smoothness, uniaxial motion, rigidity and thermal stability. In the preferred embodiment, the smoothing filter 40 is active during the second and third positioning steps of lowering the sensing probe 12 above the target surface 20.

The controller 32 may comprise hardware and/or software from a single, distributed or a combination of sources. The controller 32 may optionally be connected to a computer 34 containing memory 36 and, additionally, controller 32

outputs positional requests to X and Y control electronics (not shown), which provide X and Y positional signals to a scanning circuit (not shown) and piezo actuator 17. In the preferred embodiment of the invention, the controller 32 hardware comprises a local processor (not shown), remote processor (not shown),programmable digital signal processor (PDSP) (not shown), and PS/2 (PS/2 is a trademark of the International Business Machines Corporation) computer (not shown). Further, as the tip 19 is scanned across the target surface 20, and as the tip to target surface gap changes, the laser interferometer 30 will detect the change in vibration amplitude of the vibrating cantilever providing the voltage $V_a$ as input to the analog servo circuit 15. The analog servo circuit 15 provides a signal to the piezoel ctric element 24, to adjust the position of the tip, up or down, to maintain the original amplitude of vibration of the vibrating cantilever. A hierarchical input, process, and output diagram is provided for each of the hardware devices of the preferred embodiment and included as Table A.

TABLE A

Software control for the three phases of auto-approach:
Phase I:

### Local Processor

| Inputs | Process | Outputs |
|---|---|---|
| Commands from PDSP<br>Status from Remote<br>Internal timer<br>Commands to Remote | Task loop<br>  If timeout<br>    Stop all motion<br>End Task<br>Task look<br>  If Status from Remote<br>    Reset Timer<br>End Task<br>Task look<br>  case fast motion<br>  command from PDSP<br>    Turn on high speed<br>    clock<br>  case slow motion<br>  command from PDSP<br>    Set toggle speed to<br>    motion timer<br>  case command to forward<br>  to Remote<br>End Task | Clock lines on Inchworm<br>Status to PDSP<br>Internal Timers<br>Commands to Remote |

### Remote Processor

| Inputs | Process | Outputs |
|---|---|---|
| Position Detector<br>  (Coarse focus)<br>Position Detector<br>  (Auto approach)<br>Command from Local | Compare Algorithm<br>  Check for connections<br>  Check for Proximity<br>  Check for Noise<br>  Check for absolute<br>    Position | Status of Approach unit<br>  above/below focus<br>Inhibit/non-Inhibit<br>  of coarse positioner<br>  motion |

### PDSP

| Inputs | Process | Outputs |
|---|---|---|
| Status from Remote<br>Commands from PS/2<br>State of Inchworms | Task loop<br>  get status from<br>  Remote<br>End Task<br>Task look<br>  If command from PS/2<br>    case Get Status<br>      Send Status<br>    case Move Inchworm<br>      Forward command<br>  End If<br>End Task<br>Task loop<br>  If Signal from Feedback<br>  system lost<br>    Stop all motion on<br>    Inchworm<br>  End If<br>End Task | Status of controller<br>Motion command to<br>  Local IW control<br>Commands to Remote |

### PS/2

| Inputs | Process | Outputs |
|---|---|---|
| | | |

```
        Status from PDSP      While Auto approach      C mmands to PDSP
                              unit above focus         System Log
                                 Send Move High Speed  Display Screen
                                 command to PDSP
                              End While
                              Task look
                                 Check for communication
                                 connection with PDSP
                              End Task
                              Task look
                                 Update display
                              End Task
                              Task look
                                 Update system log
                              End Task
```

Phase II:

                                     PS/2

Inputs                  Process                   Outputs

```
Parameter Files       Get data from PDSP        Display Screen
Graphical User        Determine Threshold       PDSP Commands
   Interface             values for event       PDSP Get value commands
PDSP returned           detection               PDSP Set value commands
   Signals data       Send Threshold and event
PDSP returned           conditions to PDSP
   Status             Send "APPROACH" command
                         to PDSP
                      While Controller status
                      .NE. APPROACHED
                         Wait
                      End While
```

                                     PDSP

Inputs                  Process                   Outputs

```
Commands from PS/2    Get values from PS/2      Status to PS/2
Values from PS/2         into memory            Commands to Local
Values from DACs      Get Signal values from
                         DACs
                      Look
                         If Signal values
                         in range of threshold
                         calculated in PS/2 for
                         event set up by PS/2
                            Send Stop Motion command
                            Set Status ON SURFACE
                            Exit Loop
                         End If
                         Get Signal Values from
                         DACs
                         Command to Local for
                         Slow motion of
                         Inchworms
                      End Loop
                      Task Look
                         If Signal from Feedback
                         system lost
                            Stop all motion on
                            Inchworm
                         End If
                      End Task
```

                                     LOCAL

Inputs                  Process                   Outputs

             *********** SEE PHASE I ************

Phase III:

PS/2

Inputs

Values from PDSP
Parameter Files
User inputs

Process

Loop until dA/dD
at threshold
    Loop n times
        Vary Setpoint
        delay
        Get depth value
    End Loop
    Compute delta A/delta D
    Adjust Inchworm position
    up or down as needed
    Adjust Excitation value
    up or down as needed
End Loop

Outputs

Display screen
Commands to PDSP
Values to PDSP

PDSP

Inputs

Commands from PS/2
Values from PS/2
Values from DACs

Process

Task loop
    case Motion command
        Send Motion command
        to Local
    case Set value
        Get proper DAC value
        and send to PS/2
End Task
Task loop
    If Signal from Feedback
    system lost
        Stop all motion on
        Inchworm
    End If
End Task

Outputs

Status to PS/2
Commands to Local
Values to PS/2

**LOCAL**

In the first step of approach, the sensing probe is lowered quickly to a first position P1 above the target surface. The approaching sensing probe 12 is lowered at a relatively fast rate on the order of 2 mm/sec. The method may be that of any known method such as an optical registration or focusing method/approach, by sensing an optical focal point between the sensing probe 12 and the target surface 20.

Two separate phenomena affect the nature and amplitude of vibration of the vibrating cantilever upon further approach of the sensing probe 12 from the first position P1 to the target surface. Fig. 3 is a graphical representation of the amplitude of vibration of the vibrating cantilever vs. tip to target surface gap, illustrating the effect of the two phenomena. As illustrated in Fig. 3, an approaching sensing probe 12 exhibits an amplitude of vibration decay, or gradient, while traversing an acoustic coupling region 42, a transition region 44, and an interaction region 46. The gradient is hereafter described as the incremental change in amplitude of vibration of the vibrating cantilever 18 for each incremental change in distance of the approaching sensing probe 12. As such, the gradient is defined as (dA/dD) and may further be represented as the slope or derivative of the amplitude of vibration vs. distance curve of Fig. 3.

Setpoints or gradients along the amplitude of vibration vs. distance curve provide the controller 32 a means to position and control the sensing probe 12 above the target surface 20 as described accordingly in the preferred embodiment of the invention.

In the second step of the approach, the vibrating cantilever 18 is lowered from the first position P1 into acoustic coupling region 42 where the amplitude of vibration of the vibrating cantilever 18 is dampened as a result of an acoustic coupling between the vibrating cantilever 18 and the target surface 20. Forces on the cantilever 18 due to acoustic coupling forces change the amplitude of vibration of the vibrating cantilever 18 as the sensing probe 12 approaches target surface 20. In the preferred embodiment, the rate of approach during the second step is 100 microns/sec.

The dampening phenomenon in this region occurs as the bottom of the vibrating cantilever is brought closer to the sample surface. Air between the vibrating cantilever 18 and target surface 20 is compressed, creating air force gradi-

ents, causing the amplitude of vibration of the vibrating cantilever 18 to be dampened. The general effect of acoustic dampening is illustrated in Fig. 4. As shown, the amplitude of vibration of a dampened signal 62 is l ss than that of an undampened signal 60, while maintaining the same resonant frequency.

Accordingly, a setpoint percentage is defined as the ratio of the amplitude of vibration of the dampened vibrating cantilever to the amplitude of vibration of the undampened vibrating cantilever. In the preferred embodiment, the value of the setpoint percentage is established to result in a second position, P2. The second position P2 further defining a tip to target surface gap of approximately one to ten microns.

In the third step of the approach, the sensing probe 12 approaches the target surface 20 from the second position P2. Along with the acoustic coupling, Van der Waals force gradients change the resonant frequency of the vibrating cantilever 18 during the approach. The Van der Waals force is a spring-like force wherein atoms (not shown) at the end of the tip 12 and atoms (not shown) on the target surface 20 weakly interact. The effect of Van der Waals forces on a vibrating cantilever 18 and tip 19 is described in the article titled "Atomic Force Microscope - Force Mapping and Profiling on a Sub 100 Angstrom Scale" by Martin, et al, Journal of Applied Physics 61 (10), 15 May 1987 pp 4723 - 4729.

Once in the interaction region 46, the tip 19 is close enough to the surface that Van der Waals interaction becomes by far the most influential component influencing the amplitude of vibration of the vibrating cantilever 18. Acoustic coupling still exists, but is overwhelmed by the effect of the Van der Waals force gradient. The interaction region 46 is also characterized by much greater sensitivity of the amplitude of vibration of the vibrating cantilever as a function of tip to target surface gap. It is this increased sensitivity that is measured and used as the indicator for the final step of the automatic approach. That is, an incremental change in tip to target surface gap results in a large change in vibration amplitude of vibration in the interaction region 46. In the preferred embodiment, the rate of approach from the second position P2 toward the target surface is 10 microns/sec.

During the third step of approach, the excitation signal is first increased in order to set the amplitude of vibration of the vibrating cantilever 18 to a setpoint S. As a result, the tip 19 tends to vibrate with a larger amplitude due to the increased excitation signal. In response thereto, the analog servo circuit 15, brings the tip 19 closer to the target surface, using the piezoelectric element 24, in order to maintain a constant amplitude of vibration. The approach actuators 14 then tend to move the sensing probe 12 toward the target surface 20 while the analog servo circuit 15 tends to move the sensing probe 12 away from the target surface 20, so as to reduce the extension of the piezoelectric element 24 while maintaining the tip to target surface gap. The gradient (dA/dD) is then measured by first producing incremental changes in the amplitude of vibration of the vibrating cantilever by varying the excitation signal in an A.C. fashion. Incremental changes in tip to target surface gap results as the analog servo circuit 15 moves the tip closer to, or away from, the target surface 20 using the piezoelectric element 24. The gradient is then established as the ratio of the incremental change in amplitude of vibration of the vibrating cantilever to the incremental change in tip to target surface gap. Initially, while still in the acoustic coupling region, the gradient dA/dD will have a value approximately less than 0.0001. The above process is iterated until the gradient, dA/dD is greater than 0.01. That is, the approach is iterated until the slope is greater than 0.01. At this point the tip 19 reaches its third and final position P3, a substantially optimized scanning distance of approximately 30 Angstroms and at the desired setpoint gap.

The selection of the preferred operating frequency for the cantilever/tip assembly will be described in terms of the amplitude-frequency characteristic of the vibrating cantilever. The amplitude-frequency characteristic of an undamp-ened, vibrating cantilever is illustrated as 52 in Fig. 5a. As is typical of frequency dependent devices, the vibrating cantilever exhibits a maximum frequency, or resonant frequency, resulting in a maximum amplitude. The amplitude-frequency characteristic of a vibrating cantilever in the presence of a spring-like force (such as Van der Waals force) displays a shifted behavior 50 in Fig. 5a. Again, as with frequency dependent devices, 50 in Fig. 5a is equivalent to an amplitude-frequency curve for a device subjected to an external spring-like force. Thus, for a given frequency, a change in amplitude of vibration due to a spring-like force is predictable by comparing the change in amplitude of the two amplitude-frequency curves 50, 52 in Fig. 5a.

In the preferred embodiment of the invention, the cantilever is energized to vibrate at a drive frequency, a fraction of a percent greater than its resonant frequency. Resonant frequencies of typical cantilevers range from approximately 20 KHz to 1 Mhz. A cantilever having a resonant frequency of 400 KHz, for example, may be energized at a drive frequency of 401 KHz, illustrating an embodiment of the magnitude of the shift in frequency. When the vibrating can-tilever 18 approaches the target surface 20 forces tend to shift the resonant characteristic of the vibrating cantilever 18. Upon the imposition of this external spring-like force (such as the Van der Waals force) the change in amplitude of vibration of the vibrating cantilever is equal to the change in amplitude for the two resonant frequency curves 50, 52 for a given drive frequency. The amplitude of vibration of the vibrating cantilever will increase when the resonant fre-quency moves toward the drive frequency and, correspondingly, will decrease when the resonant frequency moves away from the drive frequency.

As illustrated in Fig. 5b, a drive frequency equal to the resonant frequency ($f_0$) yields little change in amplitude of vibration 54 for a vibrating cantilever 18 having undergone a shift in resonance. As further illustrated in Fig. 5b, a drive frequency slightly greater than the resonant frequency yields a greater change in amplitude of vibration 56 for a given

drive fr quency ($f_1$). Thus, in order to provide for a greater detectable change in amplitude, a drive frequency slightly greater than the resonant frequency is selected.

An apparatus and procedure for automatically positioning a sensing probe above a target surface has been described. The sensing probe comprises a cantilever having a microminiature tip integrally formed or mounted at one end. The cantilever is energized by a piezoelectric element which vibrates the cantilever/tip combination. The vibrating cantilever is characterized as having a resonant frequency with an amplitude of vibration determinable by a laser interferometric technique. The position of the sensing probe may be inferred by the relationship of the amplitude of vibration of the vibrating cantilever and the distance of the cantilever from the target surface. Thus, the positioning procedure is one that leads to an accurate initial positioning of the sensing tip and one in which the sensing tip does not make contact with the target surface to be imaged or measured. This automatic positioning procedure is one that is accomplished in three increasingly precise steps:

First, the vibrating sensing probe is lowered quickly to a setpoint position above the target surface, as determined by a focusing system. The method may be that of any known method such as an optical registration or focusing method/ approach.

Steps two and three of the approach utilize the amplitude of vibration of the vibrating cantilever. Namely, the position of the approaching sensing probe is controlled by tracking the amplitude of vibration of the vibrating cantilever as well as tracking an amplitude-distance gradient (dA/dD).

More specifically, in the second step of the approach, the vibrating cantilever is lowered into an acoustic coupling region. As the bottom of the vibrating cantilever is brought closer to the sample surface, air between the cantilever and target surface is compressed and the amplitude of vibration of the vibrating cantilever is dampened, while still vibrating at its operating frequency. The dampening of the vibrating cantilever throughout the acoustic coupling region is detectable. Accordingly, as the cantilever approaches the target surface, the resulting amplitude of vibration of the vibrating cantilever is processed as a percentage of the undampened signal. When a predefined setpoint percentage is reached, typically at a distance no more than one to ten microns from the target surface, the approach method switches to a final approach step which traverses the sensing probe from the acoustic coupling region through a transition region and into an atomic interaction region.

In the third step of the approach, atoms at the end of the tip and atoms on the target surface are attracted by Van der Waals forces. The Van der Waals forces are conservative, spring-like atomic forces that further attract the tip to the target surface, resulting in a shift in resonant frequency of the vibrating cantilever. Accordingly, as the cantilever further approaches the target surface, the resultant amplitude-distance gradient (DA/dD) is monitored for a desired gradient. When the desired gradient is reached, the positioning approach is complete. This final, most precise, step of the approach brings the tip to its ideal scanning distance, about 30 Angstroms from the target surface, without ever contacting the target surface.

In one of the described embodiments, a non-contact method of positioning a sensing probe, having a vibrating cantilever and tip, above a target surface includes the following steps:

Lowering the sensing probe to a first position above the target surface by a standard optical focusing method. Next, further lowering the sensing probe to a second position above the target surface, and in a region where the vibrating cantilever interacts acoustically with the target surface. Lastly, further lowering the sensing probe to a third and final position above the target surface, and in a region where the tip interacts atomically with the target surface.

The non-contact positioning of the sensing probe is critical in certain manufacturing processes, since it allows measurements to be made without damaging or destroying the product or the sensing probe. Because the probe tip does not come in contact with the target surface, samples are not changed in any way and the process eliminates losses associated with destructive testing. The measured product may then be reinserted into the manufacturing process.

The invention has been described above in connection with a preferred embodiment, including monitoring the effect of atomic interaction between a sensing probe 12 and target surface 20. The sensing probe 12, of the preferred embodiment, detects Van der Waals force interaction between the tip 19 and target surface 20. However, sensing probes of alternative scanning probe microscopes embodiments may detect such forces as electrical potential, magnetic, capacitive, or chemical potential forces. Those of skill in the art will readily recognize that alternative embodiments of the invention can be implemented by applying the method disclosed herein to include electrical potential, magnetic, capacitive, or chemical potential forces which do not depart from the scope of the invention.

## Claims

1.  A method for positioning the tip (19) of a sensing probe (12) of scanning probe microscope relative to a target surface (20), the tip (19) being mounted on a vibrating cantilever (18), the method comprising the steps of:

moving the sensing probe (12) at a first speed to a first position (P2) relative to a target surface, at which first position the sensing probe interacts acoustically with the target surface and a first predefined effect on the amplitude of vibration of the vibrating cantilever is detected by monitoring the amplitude of vibration; and moving the sensing probe (12) at a second speed which is less than said first speed to a second position (P3) between the first position (P2) and the target surface (20), at which second position the sensing probe interacts atomically with the target surface and a second predefined effect on the amplitude of vibration of the vibrating cantilever is detected by monitoring the amplitude of vibration.

2. A method according to claim 1,

wherein said detection of said first predefined effect includes determining a ratio of the amplitude of vibration of the vibrating cantilever, as dampened by acoustic interaction, to the amplitude of vibration of the undampened vibrating cantilever, and then comparing said ratio with a predetermined ratio value which is achieved at the first position; and

wherein said detection of said second predefined effect includes determining a ratio of change in the amplitude of vibration of the vibrating cantilever, resulting from a change in frequency precipitated by atomic interaction, to change in distance between the tip and target surface, and then comparing said ratio of change in amplitude to change in distance with a predefined value which is achieved at the second position.

3. A method as claimed in any of claims 1 or 2 further comprising the step of first moving the sensing probe (12) to a starting position, the starting position determined by sensing an optical focal point between the sensing probe (12) and a target surface (20), and the starting position being further away from the target surface than the first position (P2).

4. A method as claimed in any of the preceding claims wherein the first position (P2) is in the range $1.0 \times 10^{-6} - 1.0 \times 10^{-5}$m from the target surface (20) and the second position (P3) is in the range $1.0 \times 10^{-9} - 1.0 \times 10^{-8}$m from the target surface (20).

5. A method as claimed in claim 3 wherein the starting position is substantially $1.0 \times 10^{-3}$m from the target surface (20).

6. A method as claimed in any of the preceding claims wherein the sensing probe (12) is moved to the first position (P2) at a rate of approximately $1.0 \times 10^{-4}$m/sec and the sensing probe (12) is moved to the second position (P3) at a rate of approximately $1.0 \times 10^{-5}$m/sec.

7. A method as claimed in any of claims 3 or 5 wherein the sensing probe (12) is moved to the starting position at a rate of approximately $2.0 \times 10^{-3}$m/sec.

8. A scanning probe microscope comprising:

a sensing probe (12) comprising a tip (19) mounted on a vibratable cantilever (18);
means (24) for causing the cantilever to vibrate at a predetermined frequency;
means (30) for monitoring the amplitude of vibration of the vibrating cantilever; and
means (14,15), responsive to the monitoring means, for moving the sensing probe (12) at a first speed to a first position (P2) relative to a target surface (20), at which first position (P2) said means for monitoring detects a first predefined effect on the amplitude of vibration of the cantilever (18), and for subsequently moving th sensing probe (12) at a second speed to a second position (P3) relative to the target surface (20), at which second position (P3) said means for monitoring detects a second predefined effect on the amplitude of vibration of the cantilever.

9. A scanning probe as claimed in claim 8 wherein the means (24) for causing the cantilever (18) to vibrate comprises a piezoelectric bimorph coupled at one end of the cantilever.

10. A scanning probe as claimed in any of claims 8 or 9 further comprising:

means for calculating the ratio of the amplitude of vibration of the cantilever when it is dampened to the amplitude of vibration of the cantilever when it is undampened; and
means for comparing th ratio with a predefined valu .

**Rev ndications**

1. Procédé destiné à positionner la pointe (19) d'une sonde de détection (12) d'un microscope à sonde de balayage, par rapport à une surface cible (20), la pointe (19) étant montée sur une lame n porte à faux vibrante (18), le procédé comprenant les étapes consistant à :

> déplacer la sonde de détection (12) à une première vitesse vers une première position (P2) par rapport à une surface cible, à laquelle première position, la sonde de détection interagit de façon acoustique avec la surface cible et un premier effet prédéterminé sur l'amplitude de la vibration de la lame en porte à faux vibrante est détecté en surveillant l'amplitude de la vibration, et

> déplacer la sonde de détection (12) à une seconde vitesse qui est inférieure à ladite première vitesse vers une seconde position (P3) entre la première position (P2) et la surface cible (20), à laquelle seconde position, la sonde de détection subit une interaction atomique avec la surface cible et un second effet prédéfini sur l'amplitude de la vibration de la lame en porte à faux vibrante est détecté en surveillant l'amplitude de la vibration.

2. Procédé selon la revendication 1,

> dans lequel ladite détection dudit premier effet prédéfini comprend la détermination d'un rapport de l'amplitude de la vibration de la lame en porte à faux vibrante, telle qu'elle est amortie par une interaction acoustique, sur l'amplitude de la vibration de la lame en porte à faux vibrante non amortie, puis la comparaison dudit rapport à une valeur de rapport prédéterminée qui est obtenue au niveau de la première position, et

> dans lequel ladite détection dudit second effet prédéfini comprend la détermination d'un rapport de variation de l'amplitude de la vibration de la lame en porte à faux vibrante, qui résulte d'une variation de fréquence accélérée par l'interaction atomique, sur la variation de la distance entre la pointe et la surface cible, et ensuite la comparaison dudit rapport de variation d'amplitude sur la variation de distance, à une valeur prédéfinie qui est obtenue au niveau de la seconde position.

3. Procédé selon l'une quelconque des revendications 1 ou 2, comprenant en outre l'étape consistant à déplacer tout d'abord la sonde de détection (12) jusqu'à une position de départ, la position de départ étant déterminée en détectant un point focal optique entre la sonde de détection (12) et une surface cible (20), et la position de départ étant en outre plus éloignée de la surface cible que la première position (P2).

4. Procédé selon l'une quelconque des revendications précédentes, dans lequel la première position (P2) est dans la plage de $1,0 \times 10^{-6}$ à $1,0 \times 10^{-5}$ m de la surface cible (20) et la seconde position (P3) est dans la plage de $1,0 \times 10^{-9}$ à $1,0 \times 10^{-8}$ m de la surface cible (20).

5. Procédé selon la revendication 3, dans lequel la position de départ est pratiquement à $1,0 \times 10^{-3}$ m de la surface cible (20).

6. Procédé selon l'une quelconque des revendications précédentes, dans lequel la sonde de détection (12) est déplacée vers la première position (P2) à une vitesse d'approximativement $1,0 \times 10^{-4}$ m/s et la sonde de détection (12) est déplacée vers la seconde position (P3) à une vitesse d'approximativement $1,0 \times 10^{-5}$ m/s.

7. Procédé selon l'une quelconque des revendications 3 ou 5, dans lequel la sonde de détection (12) est déplacée vers la position de départ à une vitesse d'approximativement $2,0 \times 10^{-3}$ m/s.

8. Microscope à sonde de balayage comprenant :

> une sonde de détection (12) comprenant une pointe (19) montée sur une lame en porte à faux qui peut être mise en vibration (18),

> un moyen (24) destiné à amener la lame en porte à faux à vibrer à une fréquence prédéterminée,

> un moyen (30) destiné à surveiller l'amplitude de la vibration de la lame en porte à faux vibrant , et

un moyen (14, 15), répondant au moyen de surveillance, afin de déplacer la sonde de détection (12) à un première vitesse, vers une première position (P2) par rapport à la surface cible (20), à laquelle première position (P2), ledit moyen destiné à surveiller détecte un premier effet prédéfini sur l'amplitude de la vibration de la lame en porte à faux (18) et destiné à déplacer ensuite la sonde de détection (12) à une seconde vitesse vers une seconde position (P3) par rapport à la surface cible (20), à laquelle seconde position (P3), ledit moyen destiné à surveiller détecte un second effet prédéfini sur l'amplitude de la vibration de la lame en porte à faux.

9. Sonde de balayage selon la revendication 8, dans laquelle le moyen (24) destiné à amener la lame en porte à faux (18) à vibrer, comprend un cristal bimorphe piézoélectrique couplé à une extrémité de la lame en porte à faux.

10. Sonde de balayage selon l'une quelconque des revendications 8 ou 9, comprenant en outre :

un moyen destiné à calculer le rapport de l'amplitude de la vibration de la lame en porte à faux lorsqu'elle est amortie, sur l'amplitude de la vibration de la lame en porte à faux lorsqu'elle n'est pas amortie, et

un moyen destiné à comparer le rapport à une valeur prédéfinie.


**Patentansprüche**

1. Ein Verfahren zum Positionieren der Spitze (19) einer Fühlersonde (12) eines Rastermikroskops auf eine Targetoberfläche (20), wobei die Spitze (19) an einem Schwingungsausleger (18) montiert ist und das Verfahren die folgenden Schritte umfaßt:

Vorfahren der Fühlersonde (12) mit einer ersten Geschwindigkeit zu einer ersten Position (P2) relativ zu einer Targetoberfläche, wobei in dieser ersten Position die Fühlersonde akustisch mit der Targetoberfläche in Wechselwirkung tritt und durch Überwachen der Schwingungsamplitude eine erste vordefinierte Wirkung auf die Schwingungsamplitude des schwingenden Auslegers erfaßt wird; und

Vorfahren der Fühlersonde (12) mit einer zweiten Geschwindigkeit, die kleiner ist als die erste Geschwindigkeit, zu einer zweiten Position (P3) zwischen der ersten Position (P2) und der Targetoberfläche (20), wobei in dieser zweiten Position die Fühlersonde atomar mit der Targetoberfläche in Wechselwirkung tritt und durch Überwachen der Schwin-gungsamplitude eine zweite vordefinierte Wirkung auf die Schwingungsamplitude des schwingenden Auslegers erfaßt wird.

2. Ein Verfahren gemäß Anspruch 1,

in dem das Erfassen der ersten vordefinierten Wirkung beinhaltet das Bestimmen eines Verhältnisses der Schwingungsamplitude des schwingenden Auslegers, gedämpft durch die akustische Wechselwirkung, zur Schwingungsamplitude des ungedämpften Schwingungsauslegers, und dann Vergleichen dieses Verhältnisses mit einem vorgegebenen Verhältniswert, der in der ersten Position erzielt wird; und

in dem das Erfassen der zweiten vordefinierten Wirkung beinhaltet das Bestimmen des Verhältnisses der Schwingungsamplitudenänderung des schwingenden Auslegers, das sich aus einer Frequenzänderung ergibt, die durch atomare Wechselwirkung beschleunigt wird, zur Abstandsänderung zwischen Spitze und Targetoberfläche, und dann Vergleichen des Verhältnisses der Amplitudenänderung zur Abstandsänderung mit einem vorgegebenen Wert, der in der zweiten Position erhalten wird.

3. Ein Verfahren gemäß einem beliebigen der Ansprüche 1 oder 2, das ferner den Schritt des ersten Vorfahrens der Fühlersonde (12) zu einer Ausgangsposition beinhaltet, wobei die Ausgangsposition bestimmt wird durch Erfassen eines optischen Brennpunkts zwischen der Fühlersonde (12) und einer Targetoberfläche (20), und die Ausgangsposition weiter weg von der Targetoberfläche liegt als die erste Position (P2).

4. Ein Verfahren gemäß einem beliebigen der vorstehenden Ansprüche, wobei die erste Position (P2) im Bereich $1,0 \times 10^{-6}$ bis $1,0 \times 10^{-5}$ m von der Targetoberfläche (20) entfernt liegt, und die zweite Position (P3) im Bereich $1,0 \times 10^{-9}$ bis $1,0 \times 10^{-8}$ m von der Targetoberfläche (20) entfernt liegt.

5. Ein Verfahren gemäß Anspruch 3, wobei die Ausgangsposition im wesentlichen $1,0 \times 10^{-3}$ m von der Targetober-

fläche (20) entfernt liegt.

6.  Ein Verfahren gemäß einem beliebigen der obigen Ansprüche, in dem die Fühlersonde (12) zu einer ersten Position (P2) mit einer Geschwindigkeit von etwa 1,0 x 10$^4$ m/s vorgeschoben wird und in dem die Fühlersonde (12) zu einer zweiten Position (P3) mit einer Geschwindigkeit von etwa 1,0 x 10$^5$ m/s vorgefahren wird.

7.  Ein Verfahren gemäß inem beliebigen der Ansprüche 3 oder 5, in dem die Fühlersonde (12) mit einer Geschwindigkeit von etwa 2,0 x 10$^{-3}$ m/s in die Ausgangsposition vorgefahren wird.

8.  Ein Rastermikroskop, enthaltend:

    Eine Fühlersonde (12) beinhaltend eine Spitze (19), die auf einem schwingbaren Ausleger (18) montiert ist;

    Mittel (24), die bewirken, daß der Ausleger mit einer vorgegebenen Frequenz schwingt;

    Mittel (30) zum Überwachen der Schwingungsamplitude des schwingenden Auslegers; und

    Mittel (14, 15), die auf die Überwachungsmittel ansprechen, um die Fühlersonde (12) mit einer ersten Geschwindigkeit zu einer ersten Position (P2) relativ zur Targetoberfläche (20) vorzufahren, in welcher ersten Position (P2) das Überwachungsmittel eine erste vordefinierte Auswirkung auf die Schwingungsamplitude des Auslegers (18) erfaßt, und um anschließend die Fühlersonde (12) mit einer zweiten Geschwindigkeit zu einer zweiten Position (P2) relativ zur Targetoberfläche (20) vorzufahren, in welcher zweiten Position (P3) das Überwachungsmittel eine zweite vordefinierte Auswirkung auf die Schwingungsamplitude des Auslegers erfaßt.

9.  Ein Rastermikroskop gemäß Anspruch 8, in der das Mittel (24), zum Versetzen des Auslegers (18) in Schwingungen einen piezoelektrischen Zweielementkristall enthält, der an ein Ende des Auslegers gekoppelt ist.

10. Ein Rastermikroskop gemäß einem beliebigen der Ansprüche 8 oder 9, das ferner beinhaltet:

    Mittel zur Berechnung des Verhältnisses der Schwingungsamplitude des Auslegers im gedämpften Zustand zur Schwingungsamplitude des Auslegers im ungedämpften Zustand; und

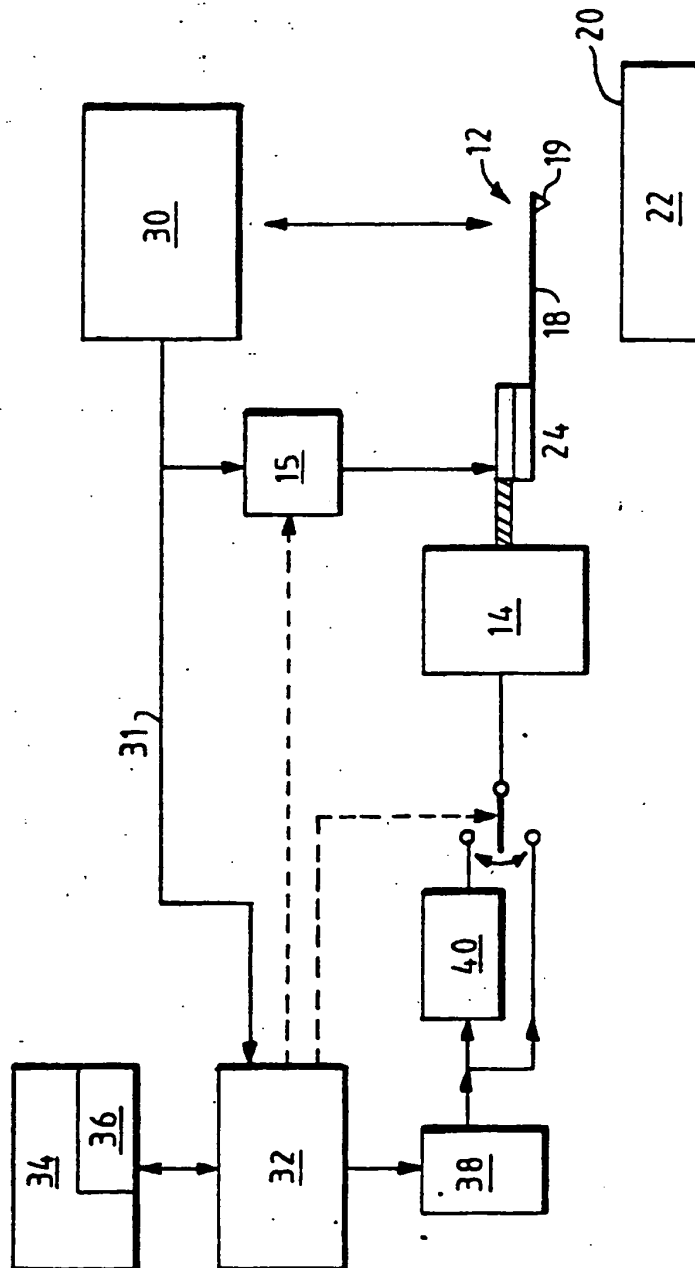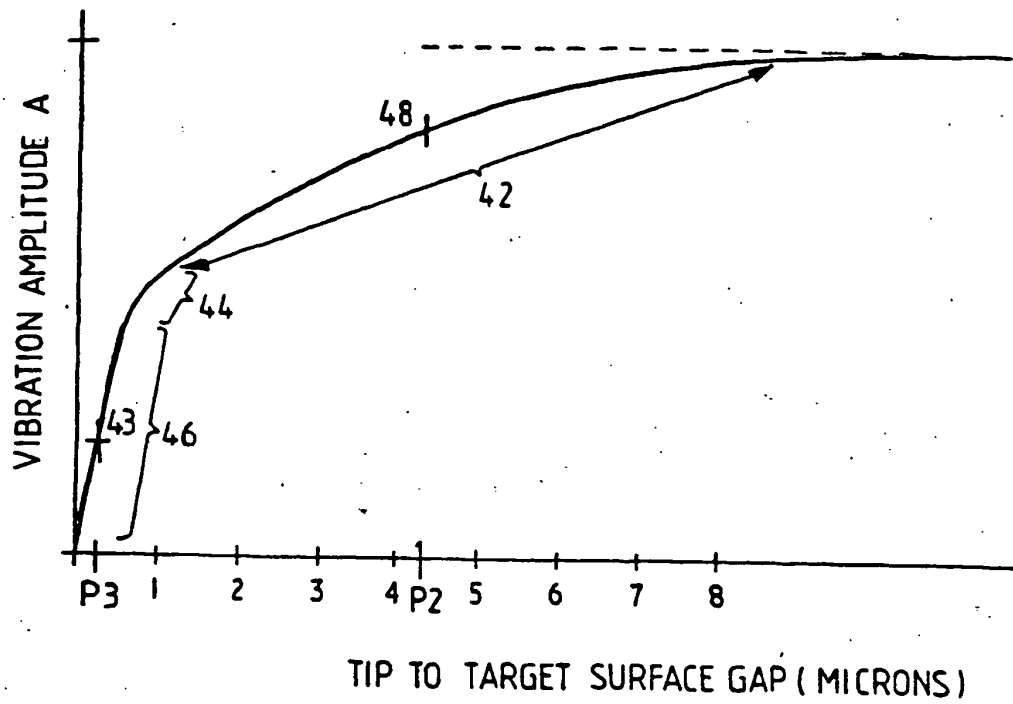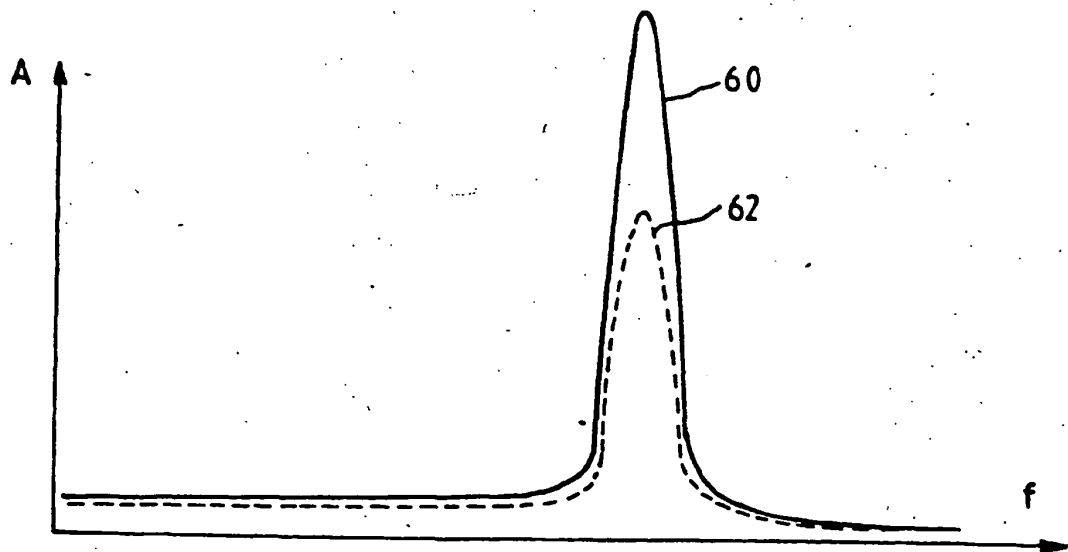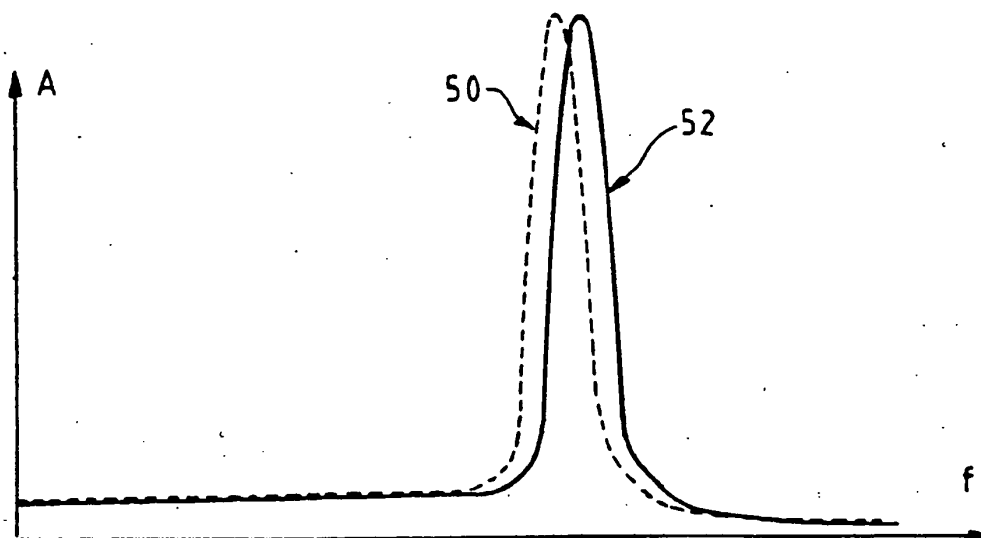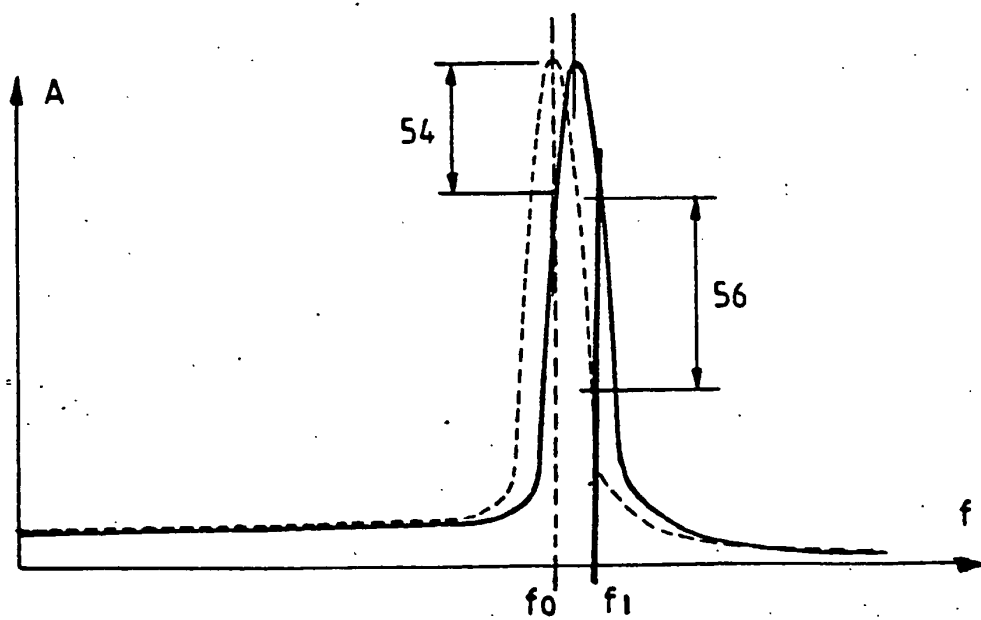    Mittel zum Vergleichen des Verhältnisses mit einem vorgegebenen Wert.
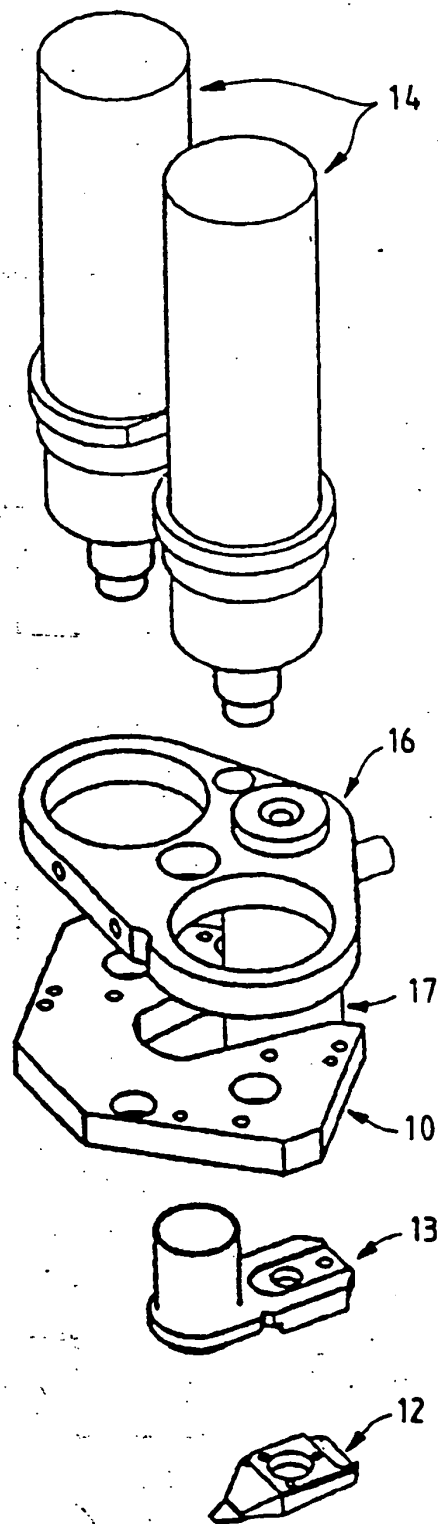
FIG. 1

FIG. 2

FIG. 3



FIG. 4

FIG. 5a



FIG. 5b